The NEPTUNE observatory as seismic warning system

*Harold Kirkham [1)] Steve Malone [2)] and John Delaney [3)]

[1)] Principal Engineer, Center for In Situ Exploration and Sample Return, Jet Propulsion Laboratory, California Institute of Technology, California, USA
[2)] Professor, Geophysics Program, University of Washington, Seattle, USA
[3)] Professor, Geology Program, University of Washington, Seattle, USA

ABSTRACT

It is proposed to install an underwater observing system off the coast of Seattle, Washington and Vancouver, British Columbia in order to allow long-term scientific study of the ocean. The area to be covered corresponds to the Juan de Fuca tectonic plate. Electric power will be provided via a cable similar to a submarine telecommunications cable, and communications will be via fiber optics in the cable. Seismic measurements will be made as part of the suite of measurements considered "community" science. The data from the seismic system could provide early warning of earthquakes for the cities of Seattle and Vancouver. This paper describes the observatory and the earthquake warning system it can support.

INTRODUCTION

For the last hundred years or so, oceanography has consisted primarily of ship-based observation. This expeditionary approach to science has recently been supplemented by satellites, which have added to the long-term capability for surface observation. The ability to make long-term observations of events in the ocean basins is, nevertheless, very limited. Many important processes are taking place in the deep water of the ocean basins: processes that control the weather and the climate, influence fish populations, and produce earthquakes. In other words, factors that affect the habitability of the planet are presently unobserved.

Motivated by the need to answer questions posed by the interplay of these various phenomena, a diverse group of scientists and engineers, led by one of us (Delaney), produced in June 2000 a feasibility study for an underwater observatory. Called NEPTUNE (originally North-East Pacific Time-series Underwater Networked Experiment), the observatory is intended to be a plate-scale system with a long operating life (NEPTUNE, 2000).

THE NEPTUNE STUDY AREA

The site selected for the NEPTUNE observatory is the Juan de Fuca tectonic plate, located off the US-Canadian west coast, as in Figure 1. The plate begins at its western edge, where there is a spreading zone, and progresses to the east, eventually going under the North American plate at a subduction zone roughly corresponding with the shoreline. This is an area about 400 km by 500 km. The variety of conditions in this area, combined with the large amount of power it is intended to make available, allow the construction of an infrastructure for studies in many sciences.

Figure 1. The NEPTUNE observatory area is between the Pacific Plate and the North American Plate.

NEPTUNE SCIENCE

There are opportunities for scientific study in many fields. The approach taken by the study team was to form a number of science Working Groups, each of which was charged with reporting on its own topic. The Working Groups' reports are summarized below.

Cross-Margin Particulate-Flux Studies

The western coast of North America is quite mountainous, and in the area of interest it receives high rainfall. The result is a large flux of sediment across the continental shelf to the adjacent deep sea floor. The characteristics of this flow of material are quite poorly known. It is planned to use NEPTUNE to study the role of the particulate flux in shaping the continental margin, and in transporting carbon and various chemicals to the deep sea.

The experiments will consist of a variety of sensors (acoustic, optical and samplers) connected to the NEPTUNE infrastructure. The initial focus will be on fine particles and the sediment-water interface at the shelf break.

Ridge-Crest Processes

The geological, chemical, physical and biological processes taking place at actively spreading mid-ocean ridges are fairly well understood. However, the details of the links between these processes, their variations with time, the degree to which ridge segments are linked and the relationship between all this and the other plate boundaries are not so well understood. The NEPTUNE observatory will make possible the long-term continuous observation of these processes and their linkages. Of interest, for example, is the relationship between heat output and fluid flow, and between these factors and any biological response.

Another area of interest is the biology of deep hot microbial life, such as that associated with seafloor volcanic eruptions and black smokers. These life-forms are ancient, and their fossils are very old (3 billion years). It may be that life on Earth originated at such locations (Rasmussen, 2000).

Subduction-Zone Processes (Fluid Venting and Gas Hydrates)

The subduction zone has two interesting aspects. The most obvious is the earthquakes, and the associated tsunamis. In addition, the zone releases as fluids at the sea floor carbon dioxide, methane, sulfide and ammonia. This fluid release is attributed to overpressure of the fluids, and the availability of escape channels in the fractured rocks. The methane in particular creates hydrates. The sudden release of trapped methane hydrates has been proposed as the cause of past climate warmings, through the greenhouse-gas effect.

It is planned to study the chemical and biological environment by connecting nutrient microprofilers, trace metal detectors and flow meters to the NEPTUNE infrastructure for extended measurement. In this field and others, the availability of underwater vehicles (autonomous underwater vehicles–AUVs–and remotely operated vehicles–ROVs) will be of great use.

Deep-Sea Ecology

It is probably fair to say that the diversity of the deep-sea biota is surprising. In recent years, several new species have been discovered associated with the black smokers. The dynamics of the interactions of the species and their nutrient supply is not well understood.

The planned observations will include optical and acoustic holography as well as imaging. There is also interest in adapting laboratory molecular techniques to the sea floor environment.

Water-Column Processes

While satellite observations provide information about the sea surface, and NEPTUNE sites will readily allow the connection of instruments on the sea floor, there remains the need to study the intervening water. NEPTUNE may allow the long-term study of large volumes of water at great spatial resolution in a number of ways. Investigators will be able to attach instruments of all kinds to bottom-mounted winch systems, to allow a bottom-up vertical profile. An array of moorings, at a spacing of 50 or 100 km, is planned for this purpose. In addition, some parameters (such as temperature and velocity) can be measured by acoustical thermometry.

Subsurface Hydrogeology and Biogeochemistry

There are a number of open boreholes across the entire Juan de Fuca Plate, drilled by the earlier (and on-going) Ocean Drilling Project. They span the complete range of geologic environments, from the sedimented ridge crest in the west, across the mid-plate area to the subduction zone in the west. By connecting instruments in these boreholes to the NEPTUNE cable system, they will serve as laboratories for studying the ocean crust.

By making long-term time-series measurements, it is hoped to expand knowledge of the interactions of the hydrologic, thermal, chemical and microbiological processes taking place.

Of particular interest to this workshop is the plan to take time-series measurements of strain and fluid pressure in holes that penetrate the primary detachment fault between subducting and overriding plates, with a view to understanding the dynamics of earthquake rupturing.

Seismology and Geodynamics

The last great earthquake along the subduction zone of the Juan de Fuca plate took place 3 centuries ago (in January 1700). A number of moderate earthquakes are taking place at other boundaries of the plate including the convergent forearc under the Seattle/Vancouver area. The fact that the center of the plate is not seismically active indicates that it is, like other plates, acting as a rigid plate, see Figure 2. The evidence would indicate that the plate is locked in the subduction zone. Thus, there is considerable interest in studying the region. In particular, insight is needed into how strain accumulates in both the land and sea portions of the system, and on the locked zone.

Figure 2. Recent earthquakes in the Juan de Fuca area, measured by a land-based seismic network

NEPTUNE ENGINEERING

To accommodate the needs of the science mentioned above, and to allow for future expansion, the NEPTUNE observatory will be built as a cabled network, capable of delivering considerable power, and to making available considerable bandwidth, at each of about 30 undersea nodes.

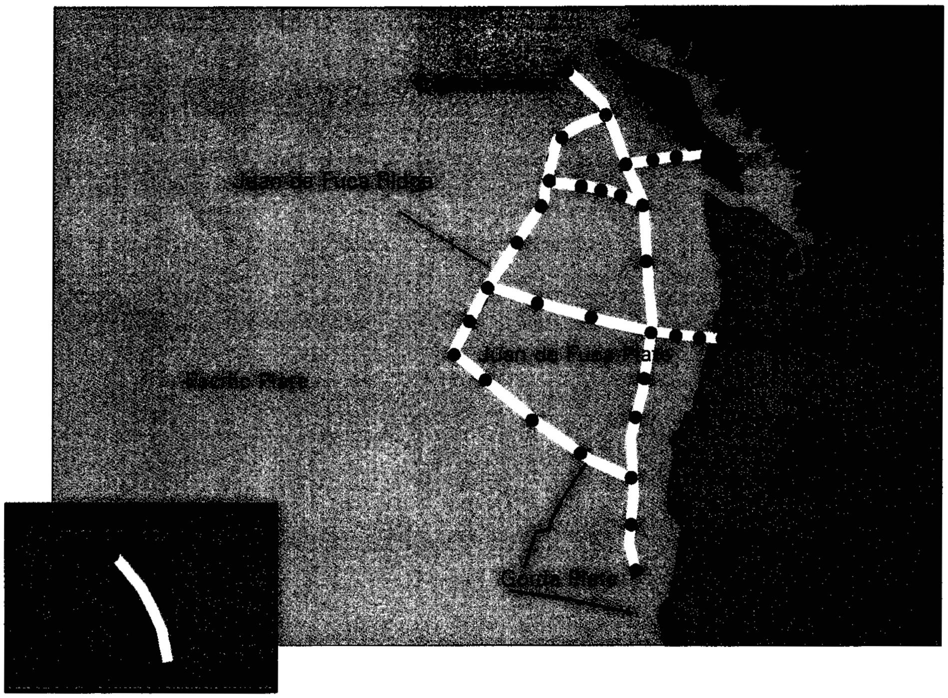

Figure 3. Layout of the NEPTUNE cable network, superimposed on the area map. The focus is the edges of the Juan de Fuca Plate

<u>Power System</u>

The power system design is constrained by the properties of the underwater cable, which will most likely be similar to a conventional submarine telecommunications cable. Because of the need to deliver more power than can be delivered by the usual approach taken in underwater cables, we have examined the limitations of the cable.

The maximum *voltage* that can be applied is around 10 kV. For the thickness of the insulation on most cables, this would seem like a low value. We infer that voids created in the insulation during manufacture would cause partial discharges at higher voltages, and limit the life of the cable. Therefore, NEPTUNE will have a maximum voltage of 10 kV.

If the size of the conductor is fixed, three factors affect the maximum *current*:

- A large value of current may cause the cable to overheat. Often this is dangerous, as burning insulation may cause a fire.
- If the cable is suspended in air between two supports, the heating caused by the current might cause the conductor to sag, and reduce clearances to nearby structures.
- If the cable run is long, the volt-drop between the source and the load may be excessive, even if the cable is operated below the level at which heating is a problem.

In the case of the power supply for NEPTUNE, volt-drop is unimportant as we can design power supplies that can operate over a wide range of inputs. Therefore, we need consider only the question of heating. In this case, the danger is not one of fire or sag, but of reducing the lifetime of the solid insulation of the cable.

Unfortunately, data are not available at present that characterize thermal performance of the cable insulation. Even if we knew the thermal conductivity and could estimate the internal temperature, we do not know how the lifetime of the insulation varies as a function of temperature. We may take comfort from the fact that the cable is immersed in a cool liquid.

We know from the manufacturers' published data that the typical submarine cable has a series resistance of around 1.5 Ω/km. Assuming that the cable conductivity is the same as for wires for house wiring, the nearest equivalent wire size seems to be US gauge #6, which has a DC resistance of 1.35 Ω/km. As a single-strand wire, this wire has a diameter of a little less than 4.7 mm. For 60 Hz AC, a single conductor in free air (which surely has worse thermal properties than water) has an ampacity (thermal limit) of 100 A.

However, at 100 A, the maximum length of cable that could be used is 67 km because the voltage limit of 10 kV would be reached. Clearly, the current must be minimized, consistent with delivering the power. This argues for a parallel power system (existing underwater cables are all series) with each load tapping off current, and using a seawater return.

The parallel system design is more complicated than a series one, but the payoff is large. With a network topology, with suitable means for switching in the event of faults, reliability is increased. With multiple power infeeds, even more power can be made available. Present plans are for the NEPTUNE system source converters to be rated at 200 kW each.

The converters at the nodes must operate with input voltages as high as 10 kV, and as low as perhaps 1 kV, delivering stable power at (say) 48 V to the user. It is planned to make about 2 kW available at each node, with more available by request. For maximum effectiveness, these converters should operate as collaborating (rather than competing) users of a limited resource (the cable). To do so, it is planned that they make use of the NEPTUNE communication system.

Communications

NEPTUNE communications will almost certainly take advantage of progress in Internet technology. As in an underwater telecommunications cable, there will be multiple single-mode fibers in the core of the cable. Unlike an underwater telecommunications cable, the NEPTUNE fibers will be tapped at many locations under the water in order to allow a science node to be connected. The overall approach is very Internet-like. The cable is therefore referred to not as a trunk, but as a *backbone*.

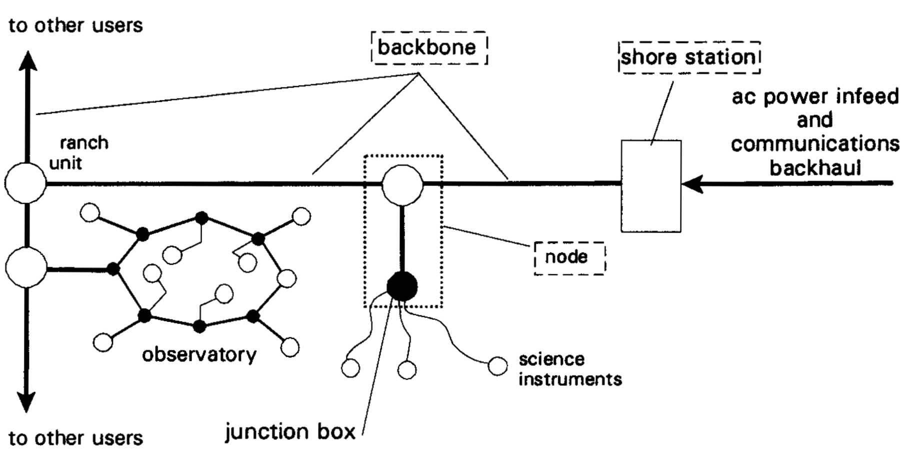

Figure 4. Representative section of the NEPTUNE backbone cable, showing taps for a node serving some science instruments and a node serving a large observatory

In order to control costs while offering significant bandwidth, it is planned to use the relatively new optical technology of gigabit ethernet (GbE). Because this technology will soon be mass-produced for land use, it is expected that costs will be considerably lower than the costs of undersea telecommunications hardware. It is planned to test a small system using GbE routers for this application in the near future. This work is being done by Alan Chave and his team at the Woods Hole Oceanographic Institute.

Essentially, the communication system will be an extension of the Internet under the ocean. The instrumentation will be accessible over the Internet from anywhere (though some level of security may be needed), and remote control and data access are planned. It is these features, combined with the possibility of local measurements, that make the possibility of an earthquake early warning scheme attractive.

NEPTUNE EARLY WARNING SYSTEM

The network of seismometers on the NEPTUNE system will include some that are located near the epicenter of a future great subduction zone earthquake. These (and similar land-based instruments) will relay their measurements to shore at internet speed. A computer system will be set up to analyze the data rapidly, and estimate the size and location of the earthquake.

Suppose there is an earthquake at the southern end of the network, as shown in Figure 4. (We choose the southern end of the rupture zone as this area has seen fewer earthquakes recently than the northern end. It happens that by placing the earthquake at the south end of the rupture zone, we create a scenario that provides the most warning time for Seattle and Vancouver.)

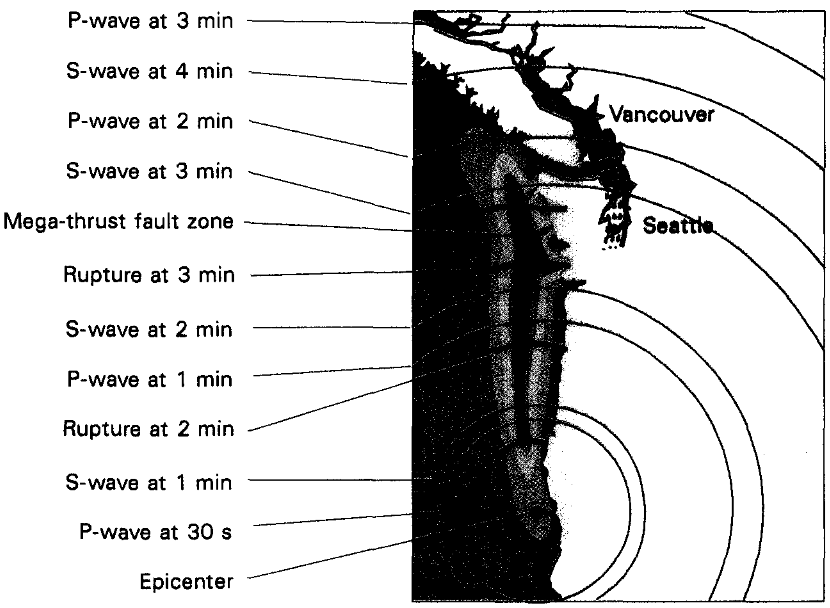

Figure 5. Potential rupture zone of a Great Cascadia Earthquake (red area).

After the earthquake begins, the fault ruptures to the north at a velocity of about 3 km/s, lagging the P- and S-waves, traveling at 6 and 3.5 km/s respectively. The shaking in Seattle is caused by waves from all parts of the fault, but the strongest shaking is due to the part of the fault nearest the city. In this situation, a warning can be generated for Seattle perhaps 4 or 5 minutes before the strongest shaking begins.

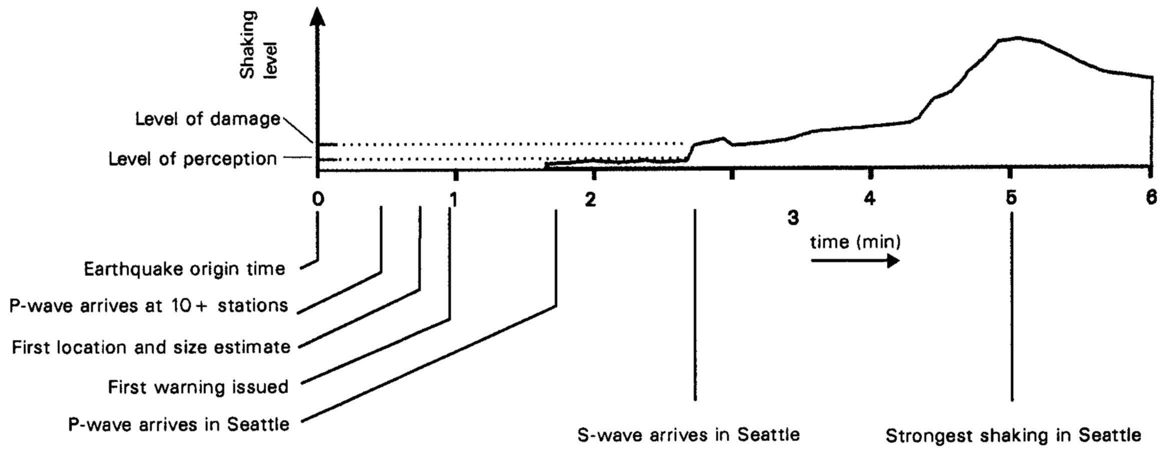

Figure 6. Earthquake and warning system activities in the first 6 minutes after the earthquake begins

As the shaking proceeds, the warning system continues to work with the seismometer information, particularly the strong-motion data, updating a "Shake Map" for the region. The product could be a color-coded map showing the severity of shaking across the region, distributed to civil authorities, the press and the public to assist in response and recovery.

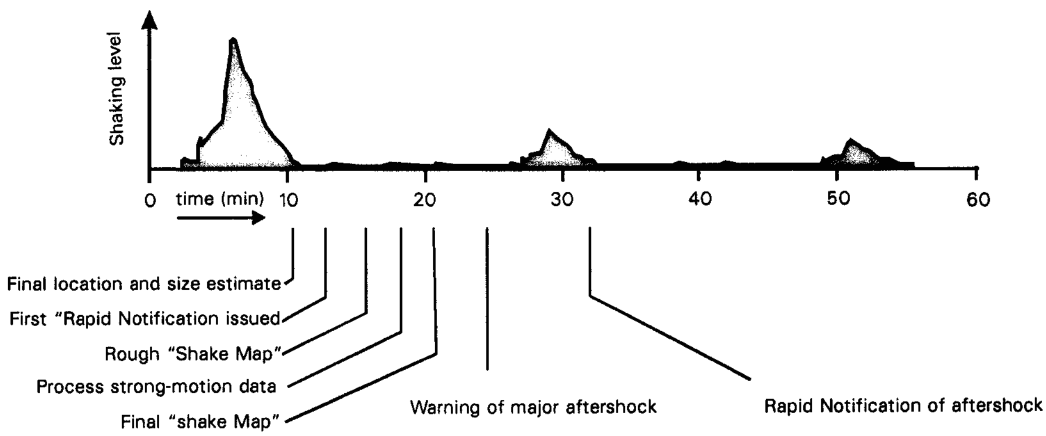

Figure 7. Earthquake and warning system activities in the first hour after the earthquake begins

Following the main shock, many aftershocks will occur, some strong enough to produce additional strong shaking in Seattle. Some of these aftershocks will have epicenter closer to Seattle, and will therefore allow less time to generate warnings.

The coordination of the NEPTUNE data with data from other systems will increase not only the value of the science obtainable but also the speed and reliability of socially relevant data products, such as the early warning system. Successful early warning and rapid notification schemes assume that seismographs and telemetry will continue to work through the period of the earthquake effects. Though the components and the system are not being designed with earthquake early warning as the primary goal, the redundant nature of the internet-like NEPTUNE network will contribute to the availability of data.

How such early warning schemes might be most effectively used for saving lives is a significant implementation issue that has yet to be fully addressed. At a minimum, gas and non-essential electricity can be turned off to prevent fires and other secondary damage to the infrastructure. Even in the event of a rupture in the zone directly west of Seattle, an advance warning of 30 seconds could be generated, and would be useful for some preventive measures.

An early warning system may be technically feasible, but would it be wise to count on it working? A few years ago there was a hurricane in the North Atlantic. Its progress was monitored as it approached the English Channel. The BBC TV meteorologist ventured the opinion that the storm would hit the French coast, and travel east. It did not: it hit the English coast, and caused considerable damage to property and injury to livestock in southern England. The public was outraged. The BBC weather-man was vilified as if he had actually caused the damage by not issuing an accurate warning. Would the same happen if an earthquake early warning scheme failed?

There are social issues worthy of further study. What is the appropriate public response to a warning? Should buildings be evacuated, or is this likely to be a problem on its own? If an early warning is available from NEPTUNE, should the authorities undertake to release the information immediately, or should it be used only to aid recovery after the earthquake?

As the construction of NEPTUNE proceeds, and before the first data are made available, the civil authorities will need answers to such questions.

REFERENCES

NEPTUNE, (2000, June) *Real-Time, Long-Term Ocean & Earth Studies at the Scale of a Tectonic Plate* Feasibility Study prepared for the National Oceanographic Partnership Program (NOPP), by the phase 1 partners: University of Washington, Woods Hole Oceanographic Institute, Jet Propulsion Laboratory and Pacific Marine Environmental Laboratory.

Rasmussen, B., (2000, 8 June) Filamentous microfossils in a 3,235-million-year-old volcanogenic massive sulphide deposit, *Nature*, Vol 405, p 676-679.

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.